# Renewable and Conventional Electricity Generation Systems: Technologies and Diversity of Energy Systems

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**Abstract** In this chapter, the primary technical aspects of conventional and renewable energy systems are presented. The description focuses on commercial systems installed across the world, together with a brief introduction to some promising technologies currently under development, such as Carbon Capture and Storage (CCS). Conventional energy systems include power plants using fossil fuels (natural gas, coal, etc.), while renewable energy systems include solar, wind, geothermal, biomass, and small-hydropower applications. These technologies are briefly described accompanied by economic figures (installation cost, fuel cost, specific cost of electricity, etc.) and emissions data (where applicable). Some insight on the energy strategy in specific countries is provided and how this can be related to local conditions and electric power requirements.

## 1 Introduction

Lately, renewable energy systems are increasingly being used for electricity generation, either at small-scale decentralized systems with capacity in the kW scale or even medium-scale systems (often called utility-scale) with capacity of a few MW. However, the large-scale systems with capacity of some hundreds of

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MW are still using conventional technologies based on fossil fuels (natural gas, coal, oil, lignite, etc.). These very large plants operate at high loads (operation at a range of 50 % to 100 % of their capacity), having high capacity factors (operation of many hours annually), and covering the base load needs of the electricity grid. One of the most important disadvantages of conventional technologies is the environmental impact. The combustion of fossil fuels leads to the inevitable production of carbon dioxide ($CO_2$), while most of the times harmful emissions are produced, such as carbon monoxide (CO), nitrogen oxides ($NO_X$), sulfur oxides ($SO_X$), unburned hydrocarbons (HC), and solid particles.

Another critical disadvantage of conventional technologies is that they need continuous fuel supply to operate, which contributes to the operating costs. This cost depends on various local and global parameters, such as fuel availability and type, fuel purity, world economic conditions, local prices, etc.

On the other hand, renewable energy technologies do not require any fossil fuel during normal operation. Their operation is based on the exploitation of natural resources, such as the sun and wind, having relatively lower operating costs, although they still require some maintenance. The most important disadvantage of renewable energy technologies is the fluctuation of their power output, which depends on the intermittency of the particular natural resource (Kosmadakis et al. 2011), which can have a significant variation, even on an hour-to-hour basis. This aspect has brought many second thoughts and skepticism on their wider implementation when energy supply must be secured, irrespective of any possible fluctuations in renewable energy resources availability.

Additionally, the installation cost (in terms of cost per installed kW) of renewable technologies is usually much higher than that of fossil fuel fired plants, bringing some restrictions on their scale and their total capacities for electricity generation. Although this cost is rapidly decreasing during the recent years, securing a lower specific energy cost (cost per kWh), and slowly approaching grid parity (specific cost equal to the electricity price for an end-user), there are still many issues to be resolved, such as excess energy storage and their safe and efficient integration to the electricity grids (Steinke et al. 2013).

The following sections introduce the mainstream commercial conventional and renewable technologies and their main characteristics and features. Cost parameters are also presented, having in mind that the cost of electricity of each technology depends a lot on the prevailing local and national circumstances, such as climate, economic, market, and even political conditions. This aspect should be considered before any techno-economic comparison is made among the different technologies.

## 2 Renewable Energy Technologies Overview

The commercial renewable energy technologies for electricity generation are briefly described next. Their main features are provided, together with an insight into their common scale and real applications.

## 2.1 Solar Energy

One of the most widely developed renewable energy sources is solar energy. Solar energy applications are constantly increasing in the last few years, and they are considered perhaps the most promising that can significantly contribute to the total electricity generation. There are two main technologies involved in the exploitation of solar energy, which differ in the way that solar radiation is harvested and converted to electricity. These are the solar photovoltaic (PV) and the concentrated solar power (CSP) technology, which are presented in the following sections.

### 2.1.1 Solar Photovoltaic Technology

Solar photovoltaic technology (PV) is the most popular technology for capturing solar energy and converting it to electricity (the solar radiation is directly converted to electricity with the use of semiconductor materials). One reason for its popularity is the modular design/size of a PV unit which has no moving parts, permitting it to be installed even on building roofs with generation capacity starting from a few Watts.

The basic element of a PV is the solar cell. There are various technologies of such cells, having a large variety of efficiency and cost. The most common solar cells are the crystalline silicon ones (either mono- or poly-crystalline), while thin films are also increasing their market share, due to their low cost and sufficient performance. Multijunction solar cells are still at a very early stage of commercialization, due to their extremely high cost and are used only in special applications (e.g., in space) and in high-concentration PV plants.

A number of solar cells form a solar panel (or solar module) with common power output of some hundreds of Watts. A PV plant consists of many such modules arranged in arrays in order to produce the required power, ranging from a few kW up to a few MW. It should be mentioned that PVs produce direct current (DC) electricity and inverters are required to convert it to alternating current (AC), decreasing somewhat their efficiency. The maximum electric efficiency of such plants at real conditions is around 10–15 %, considering also their losses at the cables, cells, and their temperature effect (Kosmadakis et al. 2011; Skoplaki and Palyvos 2009).

PV cells are also used in concentrating photovoltaic (CPV) units, where lenses or curved mirrors are used in order to increase the direct solar radiation on the PV cell surface (Kosmadakis et al. 2011). In such units, a solar tracking device is used, which traces the Sun's movement during the day. Such trackers can be also used in flat PVs, which are not very common, because of the increased maintenance and installation costs.

In CPV units, the total PV cell area per kW produced is decreased, since the incident solar radiation on the PV cell area is significantly high, making it affordable to use high-efficiency cells, such as multijunction ones (Pérez-Higueras

et al. 2011). The concentration ratio can even reach values of around 1,000 for the high-concentration configurations. A major issue in such cases is the over-heating of the PV cells, due to the high incident radiation. There are many methods to remove these large quantities of heat, either using passive ways (e.g., fins on the back of the module, applicable mainly on low-concentration systems), or active ways (e.g., using fans to cool the PV cells, for higher concentration ratios) (Kosmadakis et al. 2011; Pérez-Higueras et al. 2011). In some cases, this heat is effectively recovered and used for heating purposes, resulting to a CPV/Thermal system, which is usually installed at the kW scale and with low concentration ratios (Kosmadakis et al. 2011).

The most common way of specifying the cost of PV and any other energy production technology, is by calculating the specific cost (cost per kWh) or else *Levelised Cost Of Energy* (LCOE) (Hernández-Moro and Martínez-Duart 2013). This value for the PV technology depends on the local weather conditions, but reasonable values are in the range of 0.12–0.25 €/kWh, which are however rapidly declining the last years. The installation cost of PV plants is around 2,000–2,500 €/kW for the small-scale systems, decreasing to just 1,500 €/kW (or perhaps even below that) for the larger ones (Branker et al. 2011; Kosmadakis et al. 2011). In Fig. 1 the average cost of PV plants is depicted, which is decreasing during the last few years for both utility (of MW scale) and commercial scale (of kW scale), while the future prediction/projection includes some smaller price decrease (Branker et al. 2011; Hernández-Moro and Martínez-Duart 2013). The decrease of LCOE is actually the combined result of both price decrease and PV efficiency increase, so that its reduction is steeper and quickly approaching the grid parity in areas with high insolation, such as in the USA, China, and Spain, where the solar PV industry is also very active.

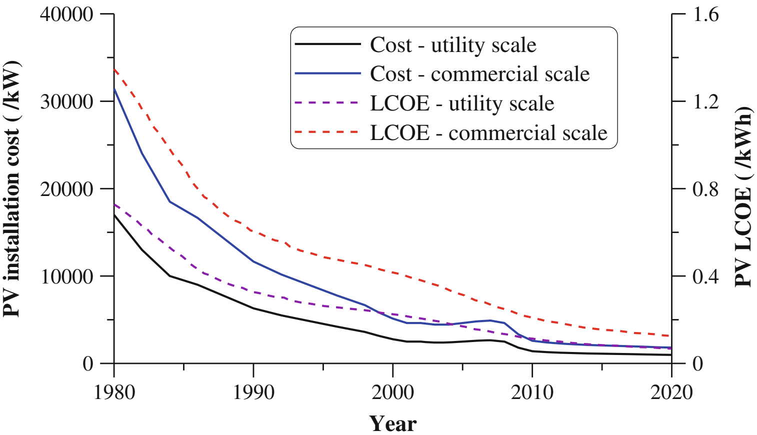


**Fig. 1** PV installation cost and levelised cost of energy (LCOE) for commercial and utility scale plants

### 2.1.2 Concentrated Solar Power Technology

Solar thermal collectors are used to capture the solar radiation, convert it to heat and finally to electric energy with the use of a heat engine. Flat plate collectors are rarely used for electricity generation, since their maximum operational temperature is usually lower than 120 °C and the resulting efficiency is too low. The most common method for power production using solar thermal technology is the concentrated solar (thermal) power (CSP) technology.

This technology concerns lenses or mirrors, which concentrate the solar radiation on the receiver, in which a fluid is circulated, heated, and then driven to the heat engine for power production. The CSP plant configurations vary, depending on the geometry and the operation of the system, as well as the solar radiation harvesting method, which can be divided into parabolic trough collector, Fresnel collector, dish Stirling collector, and the solar power tower (Viebahn et al. 2011). In all these variations, the main concept is the same, whereas the heat engine and the concentration ratio can change, bringing a variation to the operating temperature as well. The most popular CSP technologies, together with their most common commercial plant scale and efficiency are depicted in Table 1.

The solar power tower shows the highest efficiency, due to the operation at high temperature and capacities. On the other hand, its installation cost is higher than the parabolic troughs, which are today the most common CSP technology.

CSP plants are mostly of large scale with common capacities of more than 10–20 MW, since the heat engine technology used is derived from conventional plants with some proper modifications. Usually water-steam is generated and expanded in a conventional steam turbine, while a thermal-storage unit can be also included in the plant configuration to stabilize the power production and operate during the night as well. This additional feature increases the installation cost, but provides flexibility to the power production and solves some electricity grid issues that could arise. In CSP plants with capacity lower than 1 MW, the heat engine is usually an organic Rankine cycle (ORC) engine, which is the ideal technology for small/medium-scale systems (Kosmadakis et al. 2011). Finally, the solar dish Stirling unit is of kW scale and has increased concentration ratio and temperatures, making its Stirling power cycle operate with high efficiency, having unfortunately high costs. The main advantage of the Stirling Dish technology is that no cooling system is needed, making this technology more applicable for areas, where no water is available (e.g. in deserts).

**Table 1** CSP technologies and indicative plant scale and solar to power conversion efficiency

| Solar thermal technology | Scale (MW) | Solar to power conversion efficiency (%) |
|---|---|---|
| Solar dish stirling engine | 0.01–10 | 20–25 |
| Linear fresnel collector | 0.1–10 | 15–20 |
| Parabolic troughs | 1–150 | 20–25 |
| Solar power tower | 2–300 | 30–35 |

CSP plants are not very common and just lately their development has been expanded. They are mainly installed in areas, where there are significant incentives (such as in Spain and the USA) and high solar potential, preferably over 1,800 kWh/m$^2$/year of direct solar radiation. Their development started from the 80s with the Solar One and the SEGS projects in the USA (NREL 2012a) and continued with Planta Solar 10 in Spain (NREL 2012b). These two countries are the front-runners in the sector and have invested great resources on research facilities of this technology.

The LCOE of CSP plants is in the order of 0.15–0.20 €/kWh, showing a large range of installation costs of 2,000–6,000 €/kW (Hernández-Moro and Martínez-Duart 2013). These values depend on the technology used, its scale, and the possible use of a thermal storage unit, while the solar power tower and the solar dish Stirling have the highest costs.

## *2.2 Wind Energy*

Another very common renewable energy source is wind. With the use of a wind turbine (most common is the horizontal axis turbine), the kinetic energy of wind is converted to mechanical power and then to electricity. Usually, several wind turbines are installed together and constitute a wind farm. Their capacity ranges from some kilowatts up to some megawatts (the large wind farms can even reach a capacity of 100 MW), while they can be installed either on-shore (not only lower installation cost, but also lower average wind speeds) or off-shore (higher costs, but much higher average wind speeds).

A common wind farm's capacity factor is around 20–30 % (in other words, how much time per year the system operates at maximum capacity), while their installation is advised only in areas with high wind potential (e.g., high-altitude areas). This technology is very mature, since many commercial units are installed every year, and with thousands of GW already installed around the globe. Their cost is steadily declining, although with a slower rate compared to PV, and is currently equal to around 1,000–1,500 €/kW for the large on-shore units of megawatts-scale. This cost is much higher for the smaller ones (Bolinger and Wiser 2012), due to the economies of scale and for the off-shore ones, since large infrastructure is required for installing them at deep waters.

The LCOE of wind farms takes into consideration the equipment cost, the operating and maintenance (O&M) cost and the electric energy produced, while it shows a large variety, depending on the size, the location, and the wind potential. Common values are around 0.10 €/kWh or even less for large wind farms, which is highly competitive and has pushed wind farms to a fully commercialization. However, there are still some relevant research activities, mainly dealing with the development of very large wind turbines and very small ones (of few kW, appropriate to be installed in the urban environment).

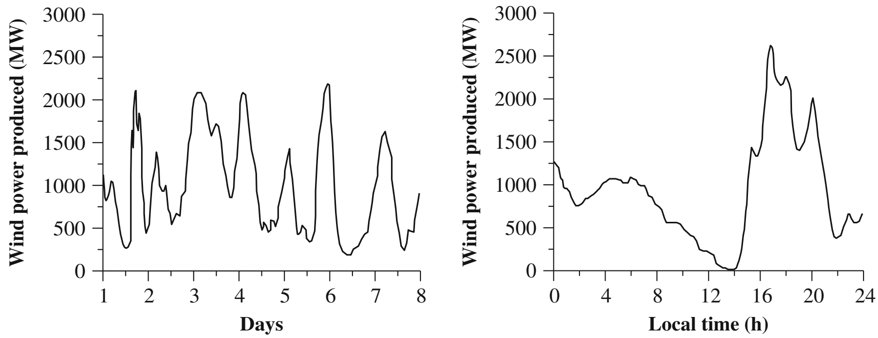


**Fig. 2** Fluctuations of wind power produced during a representative week (*left*) and day (*right*)

Today, wind farms are installed in various areas of the world, reaching a total global capacity of 300,000 MW (Bolinger and Wiser 2012) (four times higher than the total PV capacity). The main reasons for such high penetration of wind energy plants are their low costs and mature technology. On the other hand, the cost-effectiveness of such plant is influenced from the selection of the installation location which should be critically evaluated. For a specific location, a large database of wind measurements over many years should be available, before any engineering work is implemented.

The most important disadvantage of wind power plants is the strong fluctuations of the power output and the great uncertainty on prediction of wind velocity. These two factors greatly contribute to the low capacity factor of such plants. The wind velocity and power produced can become unavailable during a very short time (even within an hour), which means that at this case there should be reserved power from other type of power plants or energy storage technologies, to cover the required energy. In Fig. 2 is shown a representative power fluctuation of wind plants during a week (left chart) and during a day (right chart). Such fluctuations are very strong and reduce the flexibility of an electricity grid, which should at all times be able to cover the energy demand.

The recent world leader of wind farms is China, who is rapidly progressing during the last few years, having large wind potential. Other important global players are the USA, Germany, Spain, India, Canada, France, and many other countries of the European Union (GWEC 2013; Hu et al. 2013), which show well-developed wind industry and applications. Denmark has currently the highest wind penetration worldwide, since around 20 % of its energy production comes from wind farms, many of those being off-shore (GWEC 2013), following political decisions to focus on wind power, in order to decrease their carbon emissions and coal use. Apart from that, the wind energy industry in Denmark is very strong, supporting the installation and operation of many wind farms.

### 2.3 Bioelectricity Generation

Biomass is a renewable energy source and refers to waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, energy crops, as well as the biodegradable fraction of industrial and municipal waste that can be used as fuel for different scale power production. Its use for electricity production is "$CO_2$-free", or, in other words, "$CO_2$-neutral", since the amount of the $CO_2$ released during its utilization equals the amount, which has been assimilated from the plant during its growth (photosynthesis).

The potential of the so-far unexploited biomass for energy power, fuels, and chemicals from biomass is of increasing importance in addressing issues of global warming and sustainability. The total amount of primary bioenergy production in the 27 Members States of the European Union (EU-27) was 100.77 Mtoe in 2009 and 112.73 Mtoe in 2010 respectively with a continuous growing market, in order to meet the goals of 2020 (Jäger-Waldau et al. 2012). The bioelectricity predictions in EU-27 for 2020 are depicted in Fig. 3, where the expected bioelectricity production is shown in each EU country for solid, gaseous and liquid biomass.

Biomass can vary in composition and form according to fuel properties, cultivation, and harvesting period. The low energy content of biomass fuel imposes additional techno-economic barriers concerning availability, logistics, and replacement of food crops. The conversion of biomass can be realized with either thermochemical processes including combustion, gasification, pyrolisis, liquefaction, or biochemical processes, such as anaerobic digestion, fermentation, and enzymes.

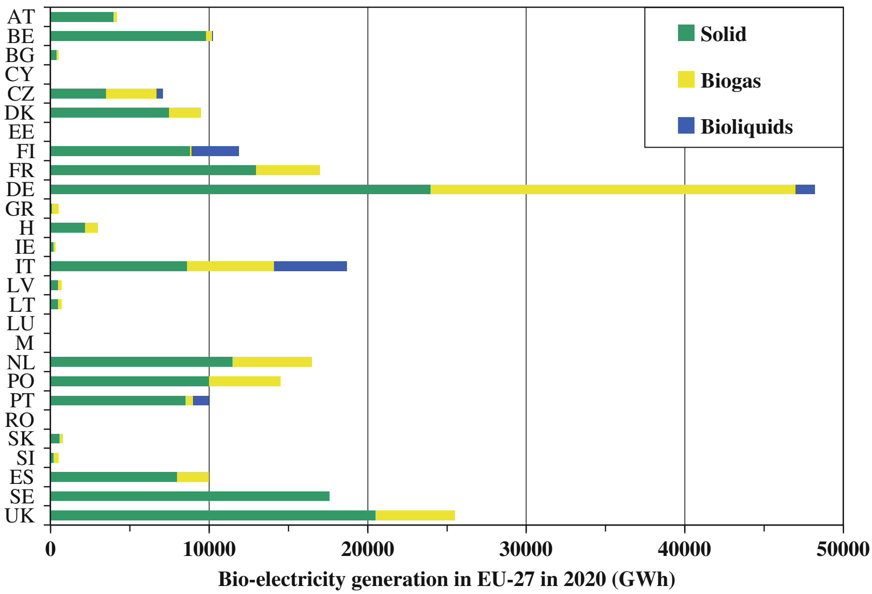


**Fig. 3** Estimation of bioelectricity generation in EU-27 by 2020 (Jäger-Waldau et al. 2012)

Biomass combustion has gained increasing attention for heat generation in domestic boilers and with respect to availability issues can find application in larger scales for electricity generation. The combustion of solid biomass usually takes place in steam or organic Rankine cycle power plants with electric efficiency in the range of 15–38 %, while it can be also co-combusted in conventional power plants, replacing some fossil fuel and reducing its $CO_2$ footprint.

Biomass thermal gasification and anaerobic digestion have attracted the highest interest amongst the biomass conversion technologies as the solid biomass can be converted to a multidiversable energy carrier gas. The produced gas is called syngas (from thermal gasification) or biogas (from anaerobic digestion) and can be exploited in emerging technologies for heat and power production and realize the decentralized energy production concept. The total global installed capacity of electricity power plants possible to be fed with raw material of renewable origin was 25.8 GW in 2008 and 28.7 GW in 2010, showing an average annual increase of about 2 GW (Jäger-Waldau et al. 2012). The available small-scale technologies for converting the biomass derived gas to electric power include internal combustion engines (ICE), microturbines, and fuel cells. Small-scale efficient combined heat and power (CHP) plants based on biomass gasification can have electrical efficiencies from 20 to 30 % of the biomass fuel lower heating value (LHV), being capable to operate for many hours per year.

Solid biomass combustion is implemented in small to medium scale plants using the technology of organic Rankine cycle (ORC), Stirling, or steam engines which however still have high costs and low efficiencies (Rentizelas et al. 2009), despite their recent commercialization. The utilization of such plants is steadily increasing, since they can operate for many hours per year with high capacity factors (depending on the fuel availability) and are considered a reliable renewable energy source, since the power production fluctuations can be minimized and controlled. The conversion efficiency decreases with the reduction of the power output, which in reverse is restrained by fuel availability and price. For power output higher than 2 MW, biomass combustion plants are used with water steam cycle reaching electric efficiencies of up to around 38 %, depending on the fuel type and the steam parameters.

For scales over 20 MW, Biomass Integrated Gasification Combined Cycle (BIGCC) technology can be used, reaching efficiencies up to 40 % (Jäger-Waldau et al. 2012). In addition, biomass is the main renewable source for liquid fuel production (such as biodiesel) used predominately in the automotive sector.

The installation cost of biomass plants is rather high due to economies of scale issues. For large steam cycle biomass plants (above 10 MW) the specific investment cost can be higher than 2,000 €/kW. For technologies used for power output lower than 2 MW, probably including ORC technology, an installation cost higher than 5,000 €/kW is expected, whereas for gasification technologies the cost is around 6,500 €/kW (for turn-key projects). The resulting LCOE is about 0.20 €/kWh depending on the fuel cost and the technology used.

In the case of biogas plants, the installation costs, including the fermenter and the internal combustion engine, are in the range of 4,500 €/kW (Karellas et al. 2010). The resulting LCOE is about 0.20 €/kWh (Stürmer et al. 2011). Taking into

consideration the power production control of such units, it is concluded that bio-energy power plants can be a highly competitive technology, especially if there is a thermal energy consumer (having a combined heat and power—CHP—plant at this case), for example a district-heating network.

Many bio-energy plants for electricity generation exist in areas where solid biomass and syngas/biogas are widely available at low cost and require little transportation. Such areas can be near forests (using wood residues) common in the USA and Scandinavian countries, agricultural areas (using agricultural waste) common in Latin America, and landfills, animal waste or energy crops for biogas production using an anaerobic digester and fuelling internal combustion engines for electricity generation, being very common in Germany (Gewald et al. 2012). It should be highlighted that although Canada has the highest solid biomass production in the world, the biofuel is usually converted to pellet and used for heating purposes and not electricity generation.

## 2.4 Geothermal Energy

The underground fluid thermal energy, called geothermal energy, can be recovered and used for electricity generation with geothermal plants. These include drilling, in order to use the hot fluids found some hundred meters below the surface of the earth. These plants are using either water at low-temperature range (over 100 °C but usually below 200 °C) and special steam turbine technology, or even a working fluid boiling at low temperature (such as pentane, R134a, R245fa, etc.), and organic Rankine cycle or Kalina technology (Campos Rodríguez et al. 2013). Due to their low-temperature operation, their efficiency is lower than 25 % depending on the technology used, but their capacity factor is high, reaching even 70–80 % (Dipippo 2004, 2012), since geothermal plants do not show significant power output fluctuations during the year, in contrast to solar and mainly wind plants. Geothermal plants are usually constructed with capacity of a few MW, although there are also some plants in the kW scale.

Their installation cost is site-specific, usually ranging from 2,000 up to 4,000–5,000 €/kW. Although these costs are high, their capability to operate for many hours per year enables them to have a low LCOE, usually lower than 0.15 €/kWh (Dipippo 2004, 2012), which is an important advantage, and can reach even values of 0.08 €/kWh for cases of high-enthalpy/temperature geothermal fields.

The low worldwide penetration of geothermal energy is mainly related to the scarcity of suitable places for construction of such plants. This fact can be witnessed by the low total installed capacity of around 12,000 MW (compared to the 300,000 MW of wind farms' capacity). USA is the world leader, while many plants also exist in Italy and Mexico (Dipippo 2012). In some areas such technology is very common for electricity and heat generation, such as Iceland, where around 25–35 % of the electricity consumption is produced by geothermal plants. Also, New Zealand and Philippines have a high geothermal energy penetration

with many installed plants and increased percentage of the total electricity generation (Dipippo 2012).

In conclusion, geothermal plants can be installed in rather limited locations, and this is the main reason why their market penetration in the renewable energy pool is increasing very slowly. Also, their high installation costs can be sometimes restrictive. On the other hand, they are reliable plants, being able to operate as base-load plants as well, and are accompanied with very low operating costs and without any fuel cost.

## 2.5 Small Hydropower Plants

There is a strong debate as to whether large hydropower plants are considered a renewable energy source or not. During their operation, a large area is flooded using a dam, significantly changing the natural environment and relocating people. For this reason, the discussion in this chapter only deals with small hydropower plants, which do not involve the construction of a dam to change the natural flow of a river. Such plants usually have a capacity lower than 10 MW (Anagnostopoulos and Papantonis 2007), while they require a careful planning and design of the installations, since the available water quantities of the river could change over time and during a year.

There are various turbine types, which can convert the gravitational energy of water to mechanical power and then to electricity with the use of a generator. The most important ones are the Pelton, Francis and Kaplan hydroturbines. All of them are suitable for specific cases and are installed after careful investigation of the available water flow rates and head (in other words the water pressure).

The LCOE of such plants is usually very low, since the operational costs are extremely low, with common values around 0.10 €/kWh, being site specific. Moreover, their installation can be accomplished with moderate values of €/kW, normally using a custom-made hydro-turbine and a large piping infrastructure (with length up to few km). Although a dam is not used to form the water reservoir (in large hydro-plants the dam construction is a large proportion of the total cost), their installation cost is usually from 2,000 up to 4,000 €/kW (ESHA 2013).

An important advantage of such plants is that they have very short response time, which means that they can start or stop operating within very few minutes. Also, they can operate for many hours per year, depending on the water flow availability. Nevertheless, the annual produced electric energy can vary each year, depending on the intensity and duration of the rainfalls. This is an important restriction for such plants, since they can even stop operating during dry months, since hydroturbines cannot operate at extreme off-design conditions with low water flow rates. The indicative water availability and electric energy produced during a typical year, together with the indicative water resources annual fluctuation is shown in Fig. 4. It should be mentioned that hydropower production is almost a linear function of the available water quantities. The peak water flow rates observed during the summer months (months 6 and 7) are due to the snow melting.

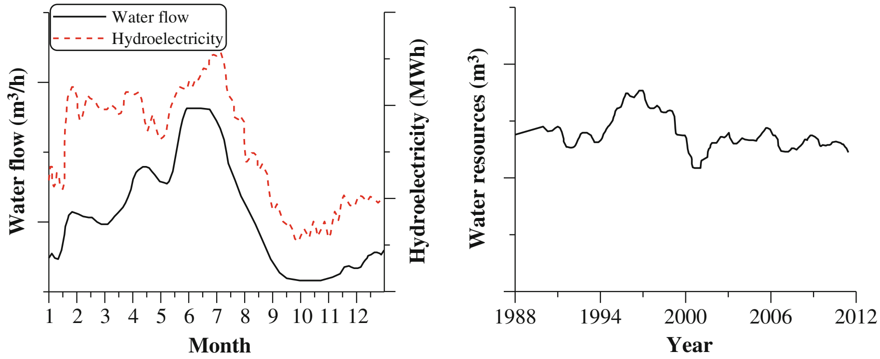


**Fig. 4** Indicative available water flow and electricity during each month (*left*) and available water resources each year (*right*)

As far as the installed hydropower is concerned, China is the world leader in small hydropower plant capacity, having more than the half global capacity, with almost 100,000 MW. Japan is a major player as well, while the USA, Canada, and many countries of Latin America have also installed many small hydropower plants, due to their increased water resources. European countries, such as Italy, France, Switzerland, and Germany, have much lower installed capacities in the range of 2,000 MW each (ESHA 2013).

### *2.6 Other RES Ready to Get Commercialized*

Ocean energy plants take advantage of the energy of waves, currents, tides or even the seawater temperature difference at different depths (most common as ocean thermal energy) and convert it to electricity with various methods. Such plants are usually off-shore and, up to now, they have been installed mainly in the UK and the USA, even at medium scale (of few MW).

Most of these projects are mostly demonstration ones, while such technology has just recently moved to commercialization. These plants are very promising, but there is still lot of research and development to be conducted, in order to decrease their costs and improve their reliability and efficiency.

## 3 Fossil Fuel Fired Power Plants

Electricity generation from fossil fuels in Europe and the rest of the world is expected to continue to play an important role in the international energy mix. Despite the increase of the renewable energy sources and their penetration in the

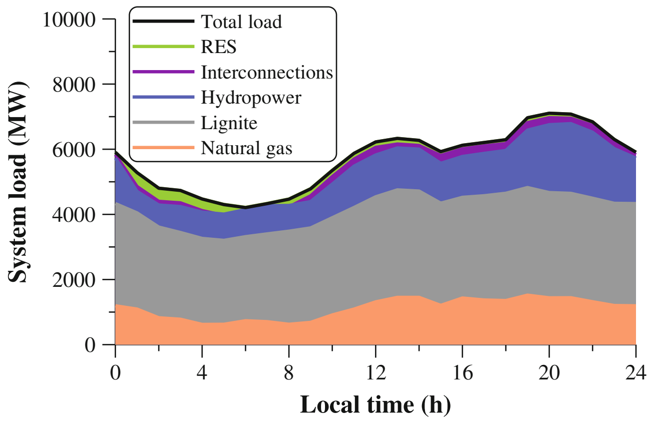


**Fig. 5** System load and energy mix during a typical winter day in Greece (IPTO 2013)

global energy mix, fossil fuels cover more than 50 % of the total electricity production. The present energy mix during a typical winter day in Greece is depicted in Fig. 5, showing the technology brake-down of energy produced (IPTO 2013). It is observed that most of the electricity produced comes from fossil-fuel fired plants, whereas the contribution of renewables is very small.

Four of the most indicative technologies for power generation are presented in this section, namely the steam power plants, the open cycle gas turbine, the combined cycle gas turbine and the internal combustion engines.

## *3.1 Coal, Lignite-Fired Steam Power Plants*

It is generally expected that coal will continue to play a key role in the future energy mix as it is the most abundant and cheapest fossil fuel source. The higher stability of the coal market compared to the oil and natural gas market, guarantees stable electricity costs, which could not be achieved without the utilization of coal as the main fuel for electricity production. Such solid fossil fuels are combusted in steam power plants, where the power cycle is based on the steam-Rankine thermodynamic cycle, using a steam turbine. These plants are widely installed in many countries, since it is the most common conventional technology.

The increase of power plant efficiency and capacity is one of the main goals of the coal industry and is directly related to the steam parameters in the boiler, seeking to increase the steam temperature and pressure. Progress in boiler design throughout the twentieth century resulted in tremendous improvements in both coal and lignite combustion and advanced steam cycles. The optimum boiler design is usually a balance between breakthroughs in combustion and metallurgy. However, the reliability of these new developments has to be also proven, since the

large-scale power plants have normally a life time of at least three decades. Furthermore, advances in emission control processes and equipment have managed the reduction of the environmental impact of the combustion process especially in the large-scale equipment. It should be noted that since the early applications of pulverized coal-fired boilers, emissions' rates have been reduced more than 300 times on a kilowatt-hour basis. Ongoing improvements are anticipated that will further improve this figure to more than 700 times.

The development of the large-scale power plant technology in the twentieth century is considered as one of the important engineering achievements. Coal, lignite pulverization, and combustion of pulverized fuel contributed to the drastic increase of installed power in large-scale power plants leading to a reduction of specific capital costs. At the same time, the progress in material science and steel manufacturing methods facilitated the development of steam boilers operating in supercritical steam parameters (above the critical conditions: 220 bar, 374 °C). This in turn led to a considerable increase of the electric efficiency and to a decrease of the electricity generation cost. Pulverized fuel firing has also contributed to the reduction of labor costs in steam power plants, increasing the flexibility of operation and allowing use of an extremely wide range of fuels, such as lignite, brown coal, hard coal, etc. The alternative, fluidized bed combustion technology, allows even higher fuel flexibility (e.g., petcoke, slurry, lignite, anthracite, etc.) with excellent environmental performance in terms of NOx and SOx emissions.

The plants' efficiency increase in the last few years was based on the progress of new high temperature resistant materials. The development of the 9 % Cr steels P91 and P92 in the late 1980s and 1990s was the result of an international effort and allowed the increase of supercritical steam parameters to the range of 300 bar and 600 °C, showing a satisfactory power plant performance in terms of reliability, flexibility, efficiency, and economy (Bugge et al. 2006). The requirements on further increase of plant efficiency and minimization of $CO_2$ emissions lead to the current research effort on the development of component materials for a 700 °C ultra supercritical power plant and on the steam cycle optimization. Brown coal pre-drying technology may play an important role toward the realization of this goal. It is estimated that the optimization of the drying process in future brown coal power plants may lead to an efficiency increase of 4–6 % points. Besides, the development of an efficient brown coal drying process is a necessary step towards the implementation of oxy-fuel firing in future generations of brown coal power plants (Agraniotis et al. 2012). One of the most advanced brown coal pre-drying technologies, currently under development, is the fluidized bed drying concept with waste heat utilization (WTA-Drying) developed by RWE (2008).

The expected plant efficiency increases through the application of lignite pre-drying technologies and supercritical parameters with 700 °C live steam temperature is shown in Fig. 6, where it is depicted that the future plants can reach an electrical efficiency of 50 % and therefore, a reduction of the $CO_2$ emissions is expected.

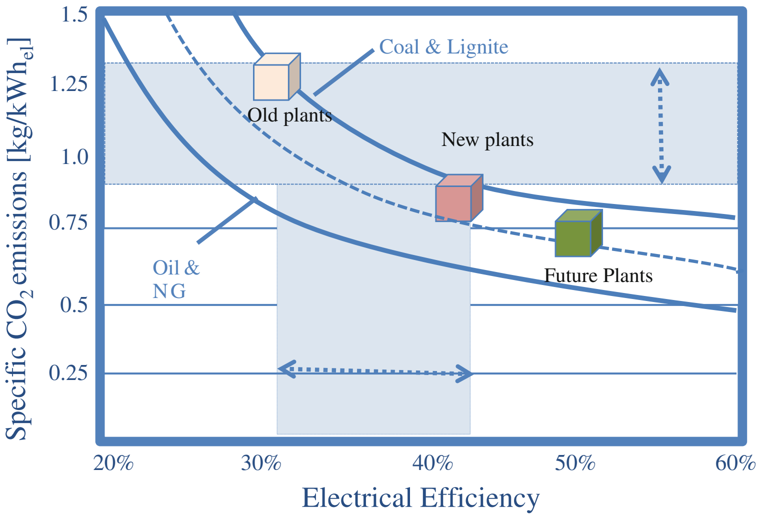


**Fig. 6** Specific $CO_2$ emissions as a function of power plant's electrical efficiency

Regarding the $CO_2$ emissions there are research activities and demonstration plants for testing the three main Carbon Capture and Storage (CCS) technologies, namely: (a) Pre-combustion capture, (b) Oxy-fuel combustion and (c) Post-combustion capture. The $NO_X$ emissions are in the range of 3,000 kg/GWh, and $SO_X$ emissions around 6,700 kg/GWh, while particle emissions around 9,000 kg/GWh (Spath and Mann 2000). These emissions are controlled with the optimization of the combustion system (air–fuel staging), DeNOx systems, desulfurization systems, and particle filters.

The electricity generation cost of such plants is calculated as the sum of the following costs: (a) annualized investment cost, (b) fuel cost, (c) fixed operating and maintenance cost, (d) variable operating and maintenance cost, and (e) costs for $CO_2$ allowances. The latter is also regarded as variable cost. An overall installation cost of 2,000 €/kW is a representative value for a state of the art Greek lignite power plant (Agraniotis et al. 2012). It should be noted that, due to different reasons related with logistics and infrastructure, the installation cost of a similar lignite plant in Central Europe may be considerably lower ranging from 1,500–1,800 €/kW. The resulting LCOE of such plants has a large variation, depending a lot on the fossil fuel costs and quality, but is usually in the range of 0.04–0.07 €/kWh.

## *3.2 Gas Turbine Plants*

Gas turbines operate with gaseous or liquid fossil fuels, usually natural gas, reaching efficiency values up to around 30–35 % (De Sa and Al Zubaidy 2011). Their capacity can range from a few (e.g., 0.05 in the case of microturbines) up to hundreds

(e.g., 250) of MW and they are a modular technology. An important advantage of gas turbines is their possibility to commence operation within a few seconds (De Sa and Al Zubaidy 2011), introducing considerable flexibility to the electricity grids, quickly covering the electricity demand and performing the so-called "peak shaving". For this reason, they can be also used as back-up power units.

Gas turbines are based on the Joule/Brayton thermodynamic cycle. Atmospheric air is driven through vents to the first component of the gas turbine, which is the axial compressor. The axial compressor significantly raises the air pressure through a number of stages to about 13–16 times the atmospheric value (De Sa and Al Zubaidy 2011) for base-load power production units. The pressurized air then enters the combustor, where fuel is injected and the combustion process takes place. The high-temperature and pressure exhaust gas then enters the turbine, where it is expanded. Its temperature and pressure drop produces mechanical power and with the use of a generator this is converted to electric power, feeding the grid.

Modern gas turbines have sustained modifications aiming at their efficiency increase. Such modifications include conducting the compression and the expansion of the working medium in two separate stages and inter-cooling or reheating it respectively in between. Another common method of increasing the gas turbine efficiency is the use of a heat exchanger to partially recover heat from the exhaust gas leaving the turbine and using it to preheat the low-temperature gas before the combustion. This process is called regeneration and can significantly reduce fuel consumption, thus increasing the overall thermal efficiency. It is mainly used in small-scale plants using single stage compressors that can be found in the so-called microturbines.

The most important factor affecting the efficiency of a gas turbine is the temperature of the exhaust gas leaving the combustion chamber and entering the turbine. The value of this temperature is usually limited by the turbine blade cooling system and the materials used, since it is necessary to avoid overheating and excess thermal stresses. For state-of-the-art technology turbines, it can reach a maximum value of about 1,300 °C.

The installation cost of gas turbines is very competitive, and is lower than 1,000 €/kW, while common values are from 400 up to 800 €/kW (Horlock 2003). Nevertheless, such plants require fossil fuels of high quality and purity for their operation, resulting to significant operational cost. The LCOE of such plants, which takes into account all kinds of costs (installation, operational, O&M, etc.), is around 0.07–0.12 €/kWh (Horlock 2003), having a large variation, depending on the fuel price, engine scale, and ambient conditions, since their performance is sensitive mostly to air temperature.

Gas turbines are being installed everywhere in the world, being most common in countries, where there is available natural gas (using preferably advanced methods of drilling and using perhaps hydraulic fracturing, known as fracking, to decrease costs and environmental concerns). They can be integrated in an electricity grid as base or auxiliary units, due to their capability to adjust their capacity to varying loads. They are very common in the Middle East and in countries where there is

scarcity of water supply, since they do not require cooling unit. Due to the combustion of high-quality fuels, gas turbines have relative low specific emissions, while the production of nitrogen oxides and sulfur oxides is minimum. The exhaust gases are mainly composed of vapor water and carbon dioxide, while some small traces of carbon monoxide are also produced, due to incomplete combustion. Typical concentrations of gas turbines emissions include $CO_2$ emissions of about 0.7–0.8 kg/KWh, 100 kg/GWh for $NO_X$, 2 kg/GWh for $SO_X$, 44 kg/GWh for $CH_4$ and 27 kg/GWh for CO (Spath and Mann 2000). These values change according to the fuel properties and total plant's efficiency and performance.

### *3.3 Combined Cycle Plants*

The exhaust gas from the gas turbines usually exits the turbine with a temperature higher than 500 °C, and can be used as heat input in a bottoming steam power cycle. In this case, a Combined Cycle (CC) is formed, where the gas turbine cycle is acting as a topping cycle and its exhaust heat feeds the heat recovery steam generator, fully or partially substituting the required fossil fuel of the bottoming steam Rankine cycle.

The efficiency of a combined cycle is actually a combination of the efficiency of the two cycles, as described next. According to the second law of thermodynamics, the efficiency of these power plants is limited from the so-called Carnot efficiency. This efficiency depends on the maximum and the minimum temperature of the power cycle. Usually, the minimum temperature is the environment, which serves as a heat sink. The maximum temperature is linked with technological operation and limitations, dealing mainly with the development of materials. The efficiency of the steam power plants, gas turbines, and combined cycle plants is presented in Fig. 7, as a function of the range of maximum temperature, depicting the Carnot limit as well.

This combined cycle efficiency depends on many parameters of the cycles, such as the combustion chamber temperature, the exhaust gas temperature from the gas turbine, the gas turbine efficiency, the live steam parameters, the condensation temperature, and the heat recovery steam generator efficiency. The ambient temperature also plays a significant role, since higher ambient temperatures lead to lower gas turbine power output and efficiency and to lower Combined Cycle Power output. Therefore and especially in hot climates, the combined cycles have air chillers which cool the inlet air temperature down to 10 °C (Kakaras et al. 2006).

The efficiency of a combined cycle can reach very high values, up to 59 %, offering high flexibility on the power contribution of the top/bottom cycles. For natural gas fueled CC plants, the installation cost ranges from 500 to about 900 €/kW (Kaplan 2008) and the cost of electricity production is around 0.06–0.09 €/kWh (Black 2010), depending on the natural gas price. The combined cycle power plants have also the possibility for additional combustion in the Heat Recovery Steam Generators (HRSG), offering the option of using solid fuels as well.

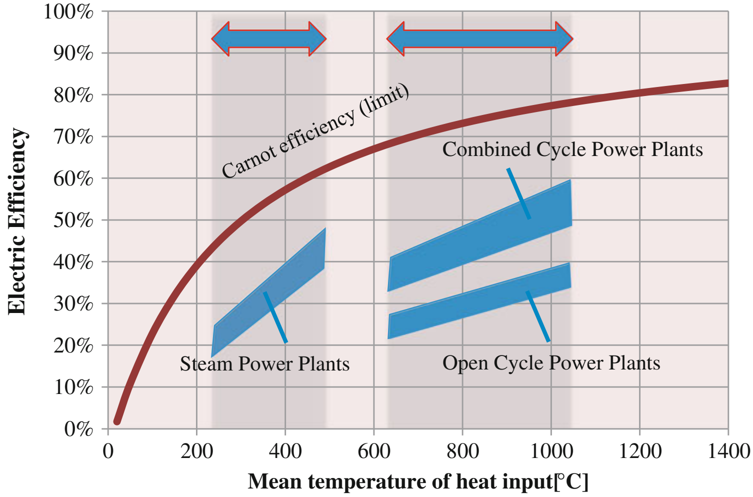


**Fig. 7** Efficiency of the three fossil-fired technologies as a function of mean temperature heat input

Most of the new natural gas fired power plants built are based on the combined cycle principle, since it has some important advantages, which were mentioned previously. Apart from the high conversion efficiency, such plants show low values of specific emissions, according to previous Fig. 6, in the range of 0.4–0.5 kg $CO_2$/kWh (Spath and Mann 2000).

Finally, it should be mentioned that hybrid solutions for the use of solar thermal energy in combined cycles can be applied in many cases. Such plants are called "Integrated Solar Combined Cycles" and solar energy is used for the production of steam, saving some amount of fossil fuel during daytime. Usually, the solar thermal power plant performs in a solar dispatching mode, where the gas turbine always operates at full load, depending only on ambient conditions, whereas the steam turbine is somewhat boosted to accommodate the thermal hybridization from the solar field (Montes et al. 2011). Integrated Solar Combined Cycle System Technology (ISCCS) is widely regarded as a "technology bridge" between fossil fuels and solar thermal energy production with some operating projects already, while many others are planned.

### *3.4 Reciprocating Internal Combustion Engines*

Internal combustion engines (ICE) are very reliable machines that are also used for electricity generation. They are usually fuelled with diesel oil, heavy oil, natural gas, or even biogas/syngas. Their capacity is usually up to some megawatts, but

with the installation of multiple units, the capacity of such plant can reach several megawatts of electric power.

They are mainly installed in isolated or autonomous areas (noninterconnected grids), including small islands. They are very popular in the Greek islands, in Middle East, and in rural areas of Canada. They are the most common prime mover in all kinds of ships, and in building installations as cogeneration plants (CHP), or even as back-up plants.

Their efficiency can be very high, reaching even values of 45–54 % for the two-stroke low-speed large engines using diesel oil, which are also turbo-charged (Henningsen 1998). The engines running on gaseous fuels have lower capacity and also lower efficiency, around 30–44 %, since they operate with lower compression ratio (EPA 2008). The installation cost of such engines can be extremely low, reaching even a cost of 300–500 €/kW for the large plants, while their LCOE is around 0.10–0.15 €/kWh (Torrero 2003). Nevertheless, for the smaller plants with capacity lower than 1 MW, these cost figures rapidly increase, due to their lower efficiency and higher cost per unit output.

A significant disadvantage of internal combustion engines for electricity generation is the high emissions produced (EPA 2008). One reason for this is the fuel used, which sometimes can be of low quality (especially for the case of heavy oil). Except from the inevitable production of carbon dioxide (around 0.5–0.7 kg/kWh), the combustion of fuel in ICEs leads to the emission of carbon monoxide (around 1 kg/MWh) sulfur oxides (around 10 kg/MWh), nitrogen oxides (around 12 kg/MWh), and most importantly to the production of unburned hydrocarbons and soot (Henningsen 1998). For most of these emissions, standards and limits have been produced (Tier standards), which are mainly applicable for maritime large-bore engines, but they are also used for on-shore large diesel engines for power production (IMO 2013). The power output and the total efficiency of the plant can be increased, when coupling the ICE engine with an ORC waste heat recovery system. In this case an increase of the power output by 10 % is expected (Gewald et al. 2012). Such systems are usually called ICE Combined cycles.

## 4 Discussion and Conclusions

The mainstream technologies for electricity generation have been presented, beginning with the renewable energy plants. Then, the conventional plants have been analyzed with specific focus on their cost, the fossil fuels utilized, and their emissions.

Although there is a common belief that RES can be applied at large scale and replace conventional power plants using fossil fuels, it has been shown that only a small fraction of the electric energy consumption is covered by renewables. Although their use is steadily increasing during the last years, their takeup is not expected to be seen the next few years. There are many issues yet to be overcome, such as the lack of cost-effective energy storage for large-scale utilities (aiding in

the security of supply) and their high installation costs, even if the latter are rapidly decreasing. To this context, great resources are given on research facilities, with a final aim to decrease the specific costs and increase the renewable energy sources penetration, not only for electricity generation, but also for heating/cooling purposes (co- /tri-generation systems). New materials, techniques, and system designs are investigated, which can further increase the efficiency. After all, the utilization of wind, solar and biomass energy is more than welcomed, which could control the produced emissions from fossil fuel fired plants in future energy scenarios.

On the other hand, the use of fossil fuels allows the generation of cheap electric energy, with good power balance management over the electricity grid. However, since carbon taxes have been finally introduced for conventional plants, and most importantly, given the uncertainty of the availability of the unexploited fossil fuel resources, the game of technologies and prices has moved toward a game of fuels governance. This game can even include efforts on increasing the conversion efficiency and the further development of carbon capture and storage technology (or even both), which can improve the environmental performance of fossil fuel plants and decrease the fuel consumed per kWh produced.

In either case, given the pure technological status of both types of technologies (renewable/conventional), the takeup of renewables does not look instant during the next few years. Still, renewables can surely play a supportive role in the energy mix, which in most countries still depends a lot on conventional power plants. And perhaps hybrid solutions (using mostly solar energy) can aid in their further introduction at larger scale, which can rapidly increase their energy share, toward the greenhouse gases emissions reduction and to a more sustainable energy future.

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